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BENEFITS OF ITERATIVE WATER SUPPLY FORECASTING IN THE WASHINGTON, D.C., METROPOLITAN AREA[1]

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ABSTRACT: The three largest water utilities in the Washington, D.C., metropolitan area (WMA) rely on the Potomac River and its reservoirs for water supply. These utilities have committed to a periodic review of the system's adequacy to meet future demands. In 1990, 1995, 2000, and again in 2004 (for publication in 2005) the utilities requested that the Interstate Commission on the Potomac River Basin (ICPRB) conduct a 20-year water demand and resource adequacy study to fulfill this need. The selection of the five-year interval provides multiple benefits. It allows regular updates and incorporation of recent demographic forecasts, and it increases visibility and understanding of the adequacy of the region's water resources. It also provides adequate time to conduct research on the physical system and to incorporate modifications based on this research into subsequent studies. The studies and lessons learned are presented in this case study of the WMA. The work has been a natural outgrowth of a long history of cooperative water supply planning and management among the main WMA water utilities and ICPRB.
(KEY TERMS: water resources planning; water demand; demographic projections; demand forecasting; resource adequacy analysis; Potomac River; consumptive use.)

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INTRODUCTION

Water supply management in the Washington, D.C., metropolitan area (WMA) requires a high degree of interjurisdictional cooperation. The urban populations in Maryland, Virginia, and the District of Columbia share the Potomac River as their primary source for municipal supply. The three major metropolitan water supply utilities, the Washington Suburban Sanitary Commission (WSSC), the Fairfax Water (FW), and the Washington Aqueduct Division of the U.S. Army Corps of Engineers (Aqueduct Division) – collectively, WMA water suppliers – jointly own water storage in upstream Jennings Randolph and Little Seneca reservoirs that they have agreed to operate for their common benefit during droughts (Figure 1). Additional regional resources include the Triadelphia and Duckett reservoirs on the Patuxent River (Patuxent reservoirs), owned by WSSC, and the Occoquan Reservoir on the Occoquan River (a tributary to the tidal Potomac), owned by FCWA, all of which are operated to improve regional water supply reliability during droughts. Water quality releases from the Savage Reservoir, owned by the Upper Potomac River Commission, also benefit the downstream WMA water suppliers during droughts.

The WMA water suppliers have committed to a periodic review of the adequacy of the system to meet future demands, by formal agreement (i.e., Low Flow Allocation Agreement of 1981 among the U.S. Army, Maryland, Virginia, Washington, D.C., the WSSC, and FW; and Water Supply Coordination Agreement of 1982 among the U.S. Army Corps of Engineers, FW, the WSSC, Washington, D.C., and the ICPRB). The first study was conducted in 1990 (Holmes and Steiner, 1990), with subsequent studies in 1995 (Mullusky *et al.,* 1996), 2000 (Hagen and Steiner, 2000), and 2005 (Kame´enui *et al.,* 2005. By request of the WMA water suppliers, the ICPRB led the effort to forecast

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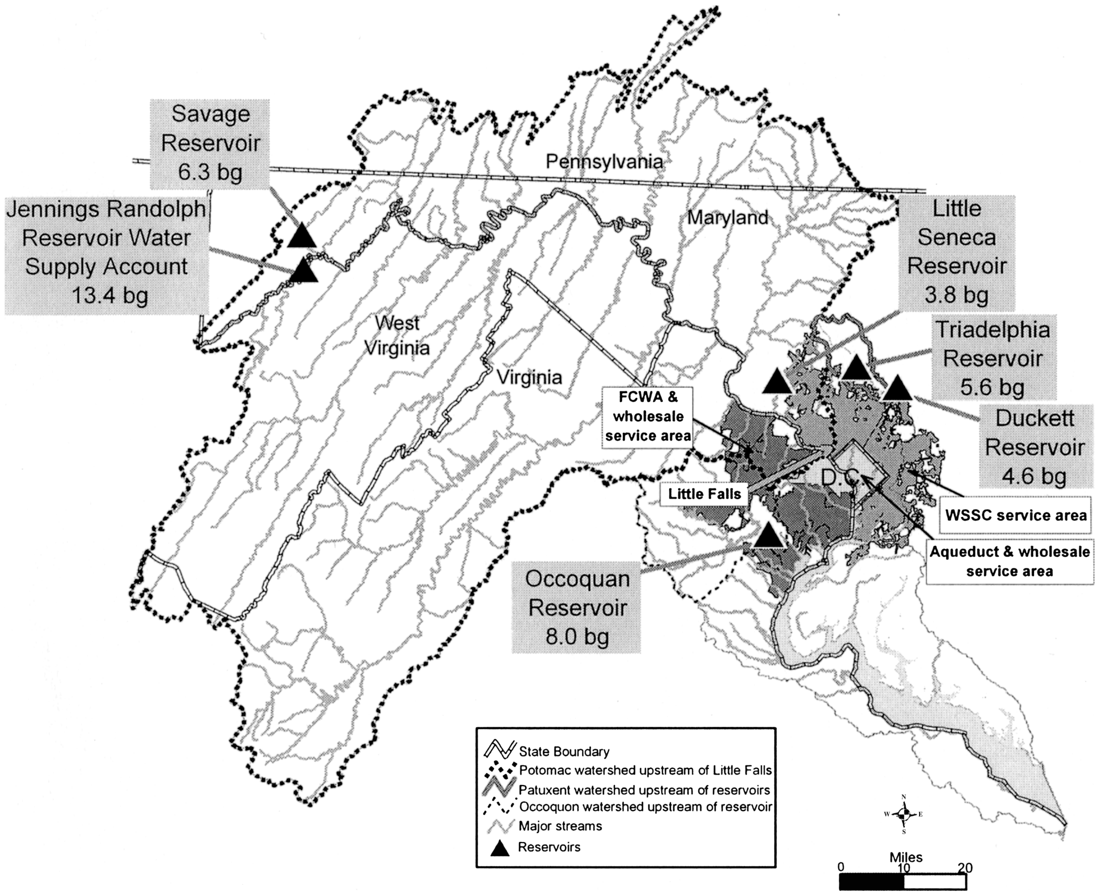

Figure 1. Potomac Basin, Patuxent Basin, Basin States, Water Supply Service Area, and Regional Supply Reservoirs.

water demand and assess resource adequacy. In cooperation with the WMA water suppliers, ICPRB developed a process to integrate the data inputs from the water utilities and regional and local planning agencies. The methods selected for both the demand forecasting and resource adequacy phases of these studies were intended to promote replication and transparency. The result is a process that is improved through periodic updates with new demographic forecasts, updated understanding of the physical system characterization, and enhancements in quantitative methodologies while relying on the same basic inputs and institutional collaborations.

THE GEOGRAPHICAL SETTING

One of the most famous landmarks of the WMA is the Potomac River. The drainage area of the Potomac includes 14,679 square miles (38,000 square km) in four states (Maryland, Virginia, West Virginia, and Pennsylvania) and the District of Columbia (Figure 1). The Potomac basin lies in five geological provinces: the Appalachian Plateau, the Ridge and Valley, Blue Ridge, Piedmont Plateau, and Coastal Plain. The majority of the basin is covered by forests at about 58 percent of the land area. Developed land makes up 5 percent of the basin, while agriculture covers 32 percent. Water and wetlands make up 5 percent of the basin.

The WMA water suppliers serve 4.1 million people in the city of Washington, D.C., and adjacent urban portions of Maryland and Virginia (Figure 1), covering an area of 1,073 square miles (2,800 square km or 7.3 percent of the watershed). The recent pattern of urban growth is similar to that of many metropolitan areas in the United States, with the suburbs and outlying towns experiencing most of the growth. The planning domain for water supply includes multiple municipalities, states, and the federal government.

DESCRIPTION OF WMA WATER SUPPLY

Most of the residents of the WMA rely on the Potomac River as their primary source of water supply. On average, the Potomac River accounts for about 75 percent of the water treated by the WMA water suppliers, with the remainder drawn from the Patuxent and Occoquan reservoirs. Average Potomac flow is about 7,000 million gallons per day (mgd; 26 million cubic meters per day or million m^3/d) with a one-day low flow (before water supply withdrawals) of 388 mgd (1.47 million m^3/d) on September 10, 1966. The annual average Potomac withdrawal for the WMA water suppliers from 2000 through 2002 was approximately 384 mgd (1.45 million m^3/d).

The WMA water suppliers collaborated to pay for storage in Jennings Randolph Reservoir and Little Seneca Reservoir, at an original cost of more than US$96 million plus annual operation and maintenance costs since construction. Costs for the Jennings Randolph Reservoir were allocated based on projections of future growth: WSSC assumed 50 percent of the costs of the new resources, FW 20 percent, and the Aqueduct Division 30 percent. The following are the major components of the metropolitan water supply system (also shown in Figure 1).

Jennings Randolph Reservoir

This reservoir provides supplemental releases to the Potomac to increase low flows and is owned and operated by the U.S. Army Corps of Engineers (USACE). The reservoir is divided into three accounts. The water supply account has 13.4 billion gallons (bg; 50.7 million m^3) that is available to the WMA water suppliers when needed. The water quality account has 16.6 bg (62.8 million m^3) that is managed by the USACE for multiple objectives including water quality and recreation. The flood control account has 11.8 bg (44.7 million m^3). Release recommendations from the water supply account are made by ICPRB based on existing and projected utility demand, status of other reservoirs, and weather conditions. The reservoir is some 200 miles (300 km) upstream of the utilities' intakes, and releases take more than a week to travel to the utilities during times of low flow.

Little Seneca Reservoir

This smaller reservoir, which stores 3.8 bg (14.4 million m^3) of water, is funded by the three utilities and is operated by WSSC. Located in Montgomery County, Maryland, releases take about a day to reach the utilities' intakes. Little Seneca is used to "fine tune" Jennings Randolph releases – without Little Seneca, water managers would have to make larger releases from Jennings Randolph to ensure adequate water supply at the intakes.

Savage Reservoir

Savage Reservoir is owned by the Upper Potomac River Commission and is operated by the USACE. This 6.3 bg (23.9 million m^3) reservoir is located in the headwaters of the basin near Jennings Randolph Reservoir. Savage Reservoir is operated primarily to maintain instream flow for industrial wastewater dilution in the North Branch Potomac. Together, Savage and Jennings Randolph reservoirs control about 3 percent of the Potomac watershed upstream of Washington, D.C. When water supply releases are made from this system, approximately 80 percent comes from Jennings Randolph Reservoir and 20 percent from Savage Reservoir.

Patuxent Reservoirs

The WSSC owns and operates two reservoirs in the neighboring Patuxent River watershed, Triadelphia Reservoir and Duckett Reservoir. Total usable storage at these reservoirs is about 10.2 bg (38.6 million m^3). The utility uses this stored water in tandem with Potomac withdrawals throughout the year.

Occoquan Reservoir

The FCWA owns and operates this reservoir on the Occoquan River, which is a tributary to the tidal Potomac estuary. The reservoir contains about 8.0 bg (30.3 million m^3) of total usable storage, which is used conjunctively with Potomac withdrawals.

This system presents opportunities for increasing efficiencies through cooperative management. Operating the reservoirs as part of a coordinated system allowed for improvement in estimated system yield via conjunctive management (Palmer, 1979). The associated synergistic gains in yield greatly increase the system's ability to meet growth. However, the system's physical characteristics also create operational difficulties. Travel times between the upstream Jennings Randolph Reservoir and the most downstream flow control point during low flows are much longer than originally assumed, making actual operations less efficient than prior model estimates (Trombley, 1982). In addition, the State of Maryland is considering a revision to the recommended minimum environmental flow at Little Falls, just downstream of the last metropolitan area water supply intake (MDNR, 2003). Any change in the recommendation could have an effect on system reliability.

HISTORY OF COOPERATION ON WATER SUPPLY

Population in the WMA grew from 672,000 in 1930 to 2 million in 1960, and forecasts in the early 1960s called for the population to grow to 5 million by 1985 (USACE, 1963). The actual MWA population realized in 1985 was less than forecast by the USACE, at approximately 3.1 million people (U.S. Census Bureau, 2004).

Drought induced rationing was a very real threat in the WMA through the 1960s and 1970s (ICPRB, 1982). In the 1963 USACE study and in subsequent water supply studies through the late 1970s, demands were forecast to exceed the low flow of the largely unregulated Potomac. Historical flows have ranged from a low of about 0.3 bgd to a high of approximately 300 bgd (Figure 2). Drought rationing in the WMA was avoided by virtue of luck, with no serious droughts threatening the water supply system in the 1970s. WMA demand levels exceeded the 1966 low flow of the Potomac River 41 times during 1971 through 1982 (Ways, 1993).

The first proposed solutions were structural, with the USACE releasing a report in 1963 recommending 16 potential reservoir sites in the Potomac River basin (USACE, 1963). The USACE study did not consider synergistic gains possible from conjunctive operation and instead calculated benefits based on independent reservoir operation. Other measures that were studied included estuary treatment plants, interconnections in the distribution systems, and interbasin transfers (Ways, 1993).

Because of financial and technical difficulties and public opposition to the structural options, the water utilities and local governments looked for other solutions. Research at Johns Hopkins University and ICPRB that began in the late 1970s showed that coordinated use of the stored water in the Potomac basin during droughts greatly alleviated the need for most new reservoirs (Sheer, 1977; Palmer *et al.,* 1979, 1982). Their research revealed that, by managing the Jennings Randolph Reservoir in coordination with the existing Occoquan and Patuxent Reservoirs, the region's projected demands could be met and adequate environmental flow could be maintained through about 2020 with only a fraction of the

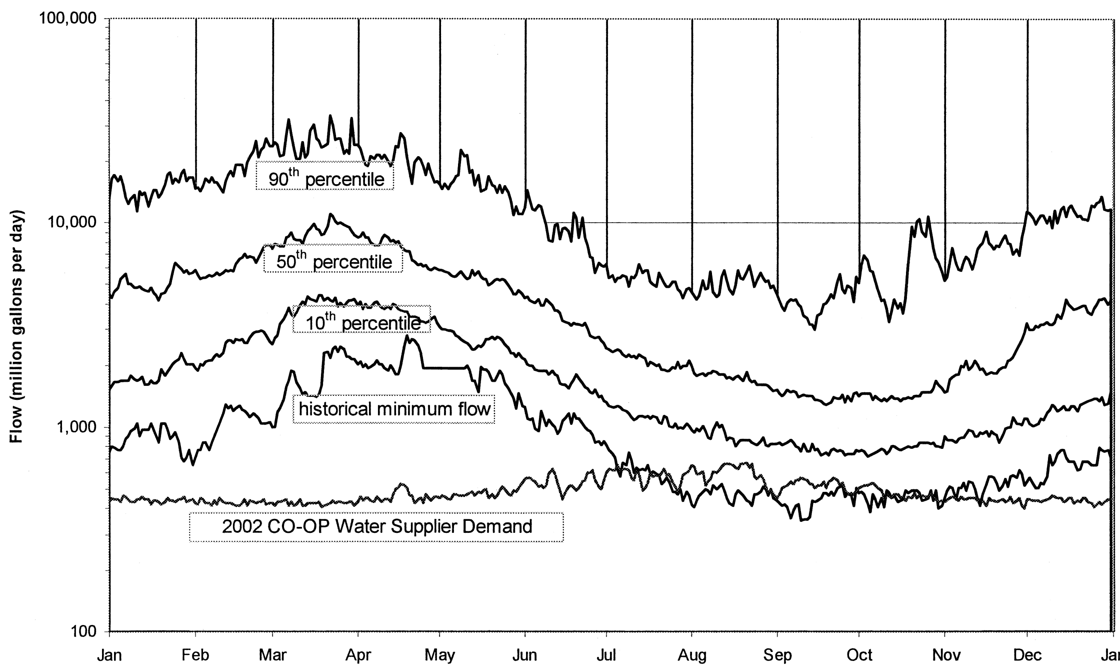

Figure 2. Flow on the Potomac River at Point of Rocks and Water Supplier Demand. Flow statistics are Based on 1895 through 2003 USGS gage flow (USGS, 2004). Data provided by T. Supple, WSSC, May 2004, unpublished data; J. Peterson, Aqueduct Division, May 2004, unpublished data; and T. Kammer-Goldberg, Fairfax Water, May 2004, unpublished data.

reservoir storage originally proposed by the USACE. Gains in reliability were obtained by operating rules that specified that the WMA water suppliers depend more heavily on the free flowing Potomac River during low flow winter and spring months in order to preserve storage in Patuxent and Occoquan Reservoirs. This strategy was physically possible because even during drought months, the winter and spring Potomac flow is more than adequate to meet water supply demands. This operating policy ensured that the Patuxent and Occoquan Reservoirs remain available for use during the summer low flow season and reduces the probability of system failure.

The WMA water suppliers institutionalized cooperative management through the 1982 Water Supply Coordination Agreement, which also designated ICPRB's Section for Co-operative Water Supply Operations on the Potomac (CO-OP) as the agency to coordinate operations. In addition, CO-OP performs an array of other water resources-related work such as drought exercises, seasonal forecasts of water supply conditions, operational and administrative support during droughts, and research (Sheer and Eastman, 1980; Sheer, 1983;Steiner, 1984; Smith, 1988, 1989; Sheer *et al.,* 1989; Steiner *et al.,* 1997, 2000).

REEMERGENCE OF WATER SUPPLY ISSUES

The issue of water resources adequacy has recently reemerged as a major concern in the WMA. After the early exploration of regional resource management at Johns Hopkins University, the construction of the Jennings Randolph and Little Seneca Reservoirs in the early 1980s, and the enactment of the Water Supply Coordination Agreement, concerns about adequacy of regional water supplies faded from prominence among policy makers and the public. The water resources available in the Jennings Randolph and Little Seneca Reservoirs were judged adequate to meet water supply demands in the eventuality of a drought in the Potomac River basin (National Research Council, 1984). Through the 1980s and almost all of the 1990s, flows in the Potomac River never dropped low enough to require releases of water from the upstream Jennings Randolph and Little Seneca Reservoirs. However, over the past six years there were two periods during which upstream reservoirs were tapped to augment Potomac River flows, including an extensive period in 2002. The droughts of 1999 and 2002, which occurred during hot, dry summers, caused a significant rise in interest in water supply management. These events, combined with the continued growth in water supply demands and potential for future resource shortfalls, prompted increased participation by stakeholders in water planning as well as greater scrutiny of resource alternatives, study methods and assumptions, and upstream water uses.

The authors of the Water Supply Coordination Agreement solved the WMA's immediate water supply need with the coordinated management solution but also had the foresight to provide a framework for studying future needs. The agreement requires water supply demands and resources to be evaluated in 1990 and every fifth year thereafter, with a forecast horizon of 20 years into the future.

METHOD FOR FORECASTING WATER SUPPLY DEMAND

A unit use coefficient approach was chosen for the WMA water supply studies in 1990 (Holmes and Steiner, 1990), 1995 (Mullusky *et al.,* 1996), 2000 (Hagen and Steiner, 2000), and 2005 (Kame´enui *et al.,* 2005) as it is a transparent and easily understandable method that can be applied to multiple jurisdictions and was judged to provide the right balance between data needs and accuracy. This is especially true in an era when the WMA's available supply of water was in excess of water supply demands.

This method is limited in that it does not account for the impact that variables such as price might have on water demand and does not allow for explicit estimation of uncertainty in the water demand estimate. Because past studies show that resources may be strained in the future due to demand growth, it is appropriate to include more comprehensive forecast methods for future studies that more explicitly incorporate uncertainty and other factors that can influence water demand. An annotated bibliography of forecasting techniques is provided by Dziegielewski *et al.* (1981). While by no means an exhaustive list, discussions of municipal water supply management including water demand forecasting techniques are provided by Baumann *et al.* (1997), Prasifka (1988), Wurbs (1994), and Mays (2003). In 2000, Planning and Management Consultants Ltd. conducted a demand forecast for the City of San Diego, California, that quantified forecast risk and uncertainty.

The unit use coefficient approach used for the WMA forecast disaggregates demand among three main categories of water uses: single family household use, multifamily water use, and employee water use. The employee water use category includes all commercial, office, governmental, and industrial water use, although industrial water use in the WMA is negligible. The main components of WMA water demand are due to single-family and multifamily residences, with significant contribution from government and office workers.

Estimates of future annual average water demands are made by applying unit use factors for each type of water use to regional demographic projections of the number of future households and employees from the Metropolitan Washington Council of Governments (MWCOG, 1988, 1994, 1999, 2004). Unit use coefficients are calculated and demographic projections are collected for 17 different geographic regions and service areas in the WMA. The 2000 study (Hagen and Steiner, 2000) and 2005 study (Kame´enui *et al.,* 2005) modified future unit use rates to account for the increasing use of more efficient plumbing fixtures.

This method of demand forecasting requires a high degree of interaction with regional water supply and other planning agencies. The most recent forecast covered the WMA water suppliers and their seven wholesale customers. Agreements by the utilities to wholesale water outside their direct service areas make it necessary to include these additional utilities in the estimation. The service areas shown in Figure 1 include the wholesale customers of each of the WMA water suppliers.

A summary of the most recent study's forecast of households, population, and employees for the WMA water suppliers' service area is shown in Table 1 (Kame´enui *et al.,* 2005), for the intermediate or "most likely" growth scenario. The forecast, based on MWCOG demographic projections from 2004 shows that households, employees, and population were projected to increase between 22 to 32 percent from 2005 to 2025 (MWCOG, 2004).

TABLE 1. Forecast of Households, Population, and Employees for the Water Supplier Service Area for the Intermediate or "Most Likely" Growth Scenario.

	2005 Estimates	Forecast For Year 2025	Percent Increase 2005 to 2025
Households	1,556,000	1,899,000	22.0
Single Family	974,000	1,160,000	19.0
Multifamily	581,000	737,000	26.9
Employees	2,612,000	3,444,000	31.9
Population	4,070,000	4,863,000	24.2

Data from Kame´enui *et al.* (2005).

The population forecasts were combined with the unit use factors to obtain a comprehensive demand forecast for the metropolitan area. WMA water supplier unit use factors for single-family households, multifamily households, and employees are shown in

TABLE 2. Unit Use Factors for 1988. 1998, and 2004.

	Aqueduct Division – Washington, D.C., Service Area	Fairfax Water – Retail Service Area	WSSC Service Area	System Average Unit Use[1]
Single-Family (gallons per day)				
1988	325	240	241	262
1998	279	227	179	214
2004	170	212	179	185
Multifamily (gallons per day)				
1988	315	177	223	236
1998	279	165	184	201
2004	160	163	175	168
Employment (gallons per day)				
1988	50	44	58	53
1998	43	44	45	44
2004	57	46	47	51

Notes: Data from Kame´enui *et al.* (2005).
[1]Weighted by relative numbers of houses or employees in DC WASA, Fairfax Water, and WSSC service areas as estimated in 1990, 2000, or 2005.

Table 2. In the 2000 demand study (Hagen and Steiner, 2000) and the 2005 study (Kame´enui *et al.,* 2005), unit use factors were projected to decrease to account for the growing use of low water using fixtures as a result of the Energy Policy Act of 1992. Unit use in the WMA is forecast to decline based on assumptions about residential water use rates (Mayer *et al.,* 1999), the number of existing households with remodeled bathrooms, bathroom fixture replacement rates, and the number of new houses with associated low flush toilets and low flow showerheads (Hagen and Steiner, 2000) (Table 3). These assumptions reduce the system average unit use by about 7 percent in year 2020 as compared to the calculated 2000 unit use rate for single-family households.

Forecasts of annual average water supply demand published in the 1990 (Holmes and Steiner, 1990), 1995 (Mullusky *et al.,* 1996), 2000 (Hagen and Steiner, 2000), and 2005 (Kame´enui *et al.,* 2005) water resource adequacy studies, as well as older forecasts from other agencies, have declined over time (Figure 3). The 2005 CO-OP forecast predicts an annual average WMA demand of 572 mgd (2.16 million m^3/d) in 2025, representing a 17 percent increase over 2005 demand levels but still less than the older forecasts. Of the CO-OP forecasts, the 1990 forecast predicts

TABLE 3. Estimated Effects of the Energy Policy Act of 1992 on WMA Toilet and Shower Household Water Use.

	1990	2000	2010	2020
Household Toilet Use, gallons per day	45	40	33	28
Household Shower Use, gallons per day	33	31	29	28
Total Household Toilet and Shower Use, gallons per day	78	71	62	56

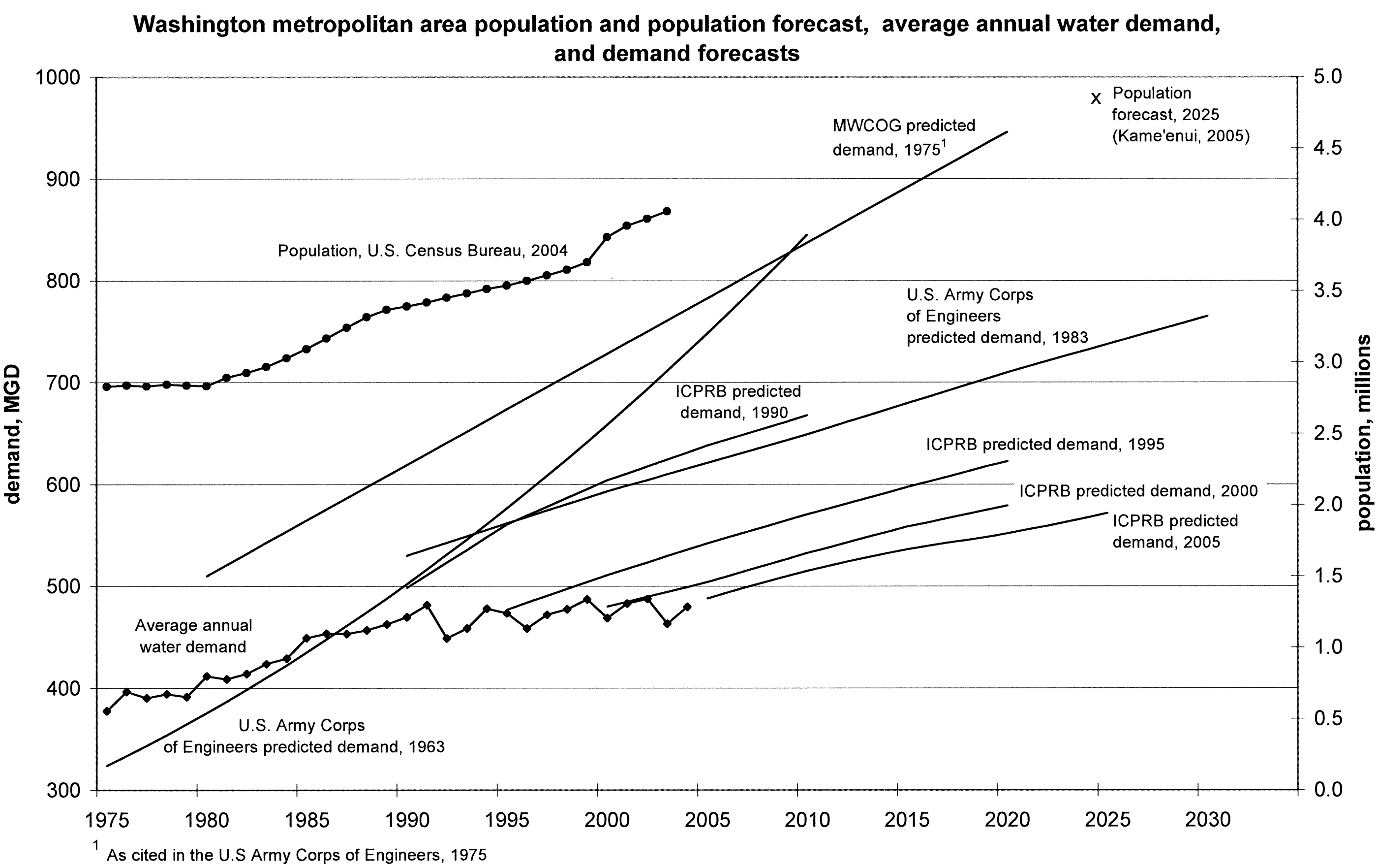

Figure 3. Washington Metropolitan Area Population, Average Annual Water Demand, and Demand Forecasts.

higher demands than both later forecasts and is higher than the demands that were actually realized.

Changes in the unit use factors and in demographics help explain the differences in the forecasts. The actual unit use factors calculated in the 1990 (Holmes and Steiner, 1990), 2000 (Hagen and Steiner, 2000), and 2005 (Kame´enui *et al.,* 2005) demand studies (based on the years 1988, 1998, and 2004) are compared in Table 2. These factors show that on average, unit use from 1988 to 2004 dropped by 29 percent for single-family housing, by almost 29 percent for multi-family housing, and by about 4 percent for employees. Changes in demographic information account for a portion of the remaining difference in forecasts. The household and employee forecasts for the 1990 (Holmes and Steiner, 1990) and 2000 (Hagen and Steiner, 2000) water demand studies are compared in Table 4. The numbers of households and employees were forecast in 1990 to be higher than those actually realized, with the number of system households in 2000 about 6.4 percent less than predicted in the 1990 study (Holmes and Steiner, 1990) and the numbers of employees about 11.3 percent less.

The slopes of the first three ICPRB forecasts are nearly identical in Figure 3, and while the forecasts were shifted down at each reevaluation, it appears that the results contradict the historical data, which show a clear concave downward trend and clearly indicate that growth in demand has leveled off in recent years. This trend is contrary to the relatively constant rate of population growth. In addition, all water demand forecasts for the WMA from the 1970s through the 1990s overpredict demand (Figure 3).

Water managers in the WMA have voiced a preference for conservative estimates of variables that become factors in the water demand forecast, especially in the face of the rapid growth experienced in the WMA (Figure 3). For example, water utility technical staff in the WMA discouraged CO-OP from adjusting unit use rates to account for the effects of the federal Energy Policy Act for the 2005 study. The staff preferred to plan for the higher estimate of future demands and viewed their preference as reflective of their responsibility to provide a safe and reliable source of water supply. Additionally, staff cited climate variability and the possibility of droughts that are worse than those recorded as reasons to estimate demands conservatively. While these factors are conservative, water managers must balance the risk of inadequate water service with the possibility of excess capacity and associated unnecessarily higher costs.

TABLE 4. Household and Employee Forecasts.

	Number of Households by Forecast Year			**Number of Employees by Forecast Year**		
	1990	**2000**	**2010**	**1990**	**2000**	**2010**
			Washington Aqueduct Division			
1990 Study	390,395	410,014	421,405	1,033,627	1,173,505	1,267,627
2000 Study	379,155	368,702	395,599	1,043,799	1,006,502	1,119,352
Difference (percent)	-2.9	-10.1	-6.1	1.0	-14.2	-11.7
			Fairfax Water			
1990 Study	370,240	482,971	539,508	416,362	626,406	785,989
2000 Study	361,276	455,882	551,776	460,011	614,250	774,132
Difference (percent)	-2.4	-5.6	2.3	10.5	-1.9	-1.5
			Washington Suburban Sanitary Commission			
1990 Study	509,320	594,772	662,749	700,586	874,181	1,043,860
2000 Study	503,120	568,455	638,880	696,250	751,561	894,460
Difference (percent)	-1.2	-4.4	-3.6	-0.6	-14.0	-14.3
			System Total			
1990 Study	1,269,955	1,487,757	1,623,662	2,150,575	2,674,092	3,097,476
2000 Study	1,243,551	1,393,039	1,586,255	2,200,060	2,372,313	2,787,944
Difference (percent)	-2.1	-6.4	-2.3	2.3	-11.3	-10.0

Note: Data from the 1990 Study (Holmes and Steiner, 1990) and the 2000 Study (Hagen and Steiner, 2000).

Conducting these studies on a regular five-year interval provides a mechanism for updating the unit use factors and demographic forecasts. While earlier forecasts may have been too high, the forecast interval of five years allows an opportunity to modify projections as demographic forecasts and water use rates change.

METHOD FOR ASSESSING RESOURCE ADEQUACY

The resource analysis is used to determine how well the regional resources can meet the forecasts of future demands. The method used for this analysis evolved from simple comparisons of cumulative deficits versus total system resources (Holmes and Steiner, 1990) to the use of the Potomac Reservoir and River Simulation Model (PRRISM) in later years. PRRISM simulates coordinated management of the reservoirs and incorporates associated conjunctive gains in system resources (Prelewicz, 2004). Assessing conjunctive gains is an important improvement in the resource analysis because it allows the efficiency gains from cooperative management to be incorporated into the analysis (Hirsch *et al.,* 1977; Palmer *et al.,* 1979). It also provides a more realistic representation of how the system would operate during drought conditions.

PRRISM is a deterministic simulation model that incorporates the daily operating rules of the system of reservoirs for the WMA. The original version of PRRISM, called the Potomac River Interactive Simulation Model, was developed at Johns Hopkins University by Richard Palmer and colleagues (Palmer *et al.,* 1979). This model was instrumental in obtaining consensus for the cooperative arrangement agreed to in the Water Supply Coordination Agreement. The most recent version of PRRISM was developed for the demand and resource studies using the object-oriented programming language Extend™ (Imagine That!, 2005) and is conceptually similar to the original model developed in the late 1970s; both models use a water balance at the reservoirs and simulate flows over the period of record.

PRRISM models Jennings Randolph Reservoir in the headwaters of the Potomac River basin, Little Seneca Reservoir in the WMA, and Potomac flow upstream and downstream of the WMA. PRRISM also models the Occoquan and Patuxent reservoirs, which provide about 25 percent of the total water supplied in the WMA. An outline of PRRISM's modeling components, inputs, and outputs is presented in Table 5. The model can be used to determine how the current or modified system of reservoirs and the Potomac River would respond to current or future demands given the current reservoir operating procedures and the historical record of streamflow.

TABLE 5. Inputs and Outputs for the Potomac River and Reservoir System Model (PRRISM).

Modeled System Components	**Inputs**	**Outputs**
Reservoirs • Jennings Randolph • Savage • Little Seneca • Patuxent • Occoquan	• Historic Streamflow (1929-2002) • Historic Reservoir Inflow • Forecast Year (annual demand as determined by demand study)	• Daily Reservoir Volumes • Reservoir Release Rates • Overall Efficiency of the Jennings Randolph and Seneca Releases • Number of Days of Releases • Potomac River Flow Upstream and Downstream of the Water Supply Intakes
Water Withdrawals For • Washington Aqueduct Division • Fairfax County Water Authority • Washington Suburban Sanitary Commission	• Seasonal Demand Pattern (choice of simulating different years' patterns of daily demand) • Choice of water supply alternatives • Restriction Percentages and Trigger Level	• Potomac "Natural" Flow (that flow unaffected by upstream human activities) • Magnitude and Frequency of Low Flows

PRRISM is run in a continuous mode through 72 years of historical reservoir inflow and Potomac River flow records on a daily time step. Continuous modeling allows for an examination of the effects of multi-year droughts on reservoir storage. The drought of 1930 to 1931 is the longest drought included in the historical record, lasting from the summer through the fall and winter of 1930 to 1931 and causing the largest depletion of modeled storage. The 1966 drought was not as lengthy but resulted in the lowest adjusted Potomac River flow of 388 mgd (1.47 million m^3/d) as calculated by the United States Geological Survey (USGS) for the Little Falls gage (USGS, 2001). The 388 mgd (1.47 million m^3/d) flow is equal to a gage flow of 98 mgd (0.37 million m^3/d) plus upstream diversions of 290 mgd (1.10 million m^3/d) for municipal use.

Seasonal demands in the WMA are also highly variable; the extremes include summer demands during the 1990s rising to as much as 741 mgd (2.80 million m^3/d) in June 1999, a drought year, and in winter periods dropping down to as low as 348 mgd (1.32 million m^3/d) in January 1993. Given this range of demands, assessing the adequacy of WMA resources is dependent on modeling the daily and seasonal demand pattern in PRRISM.

Forecasts of annual average demands are converted to forecasts of daily patterns of demand by using a model that relates historical weather and other variables to daily demand.

Daily variability in demands affects the efficiency of upstream reservoir releases. Reservoir releases from Jennings Randolph can take up to nine days to reach the intakes, and in a nine-day time frame, historical system demand has dropped by as much as 242 mgd (0.916 million m^3/d) (August 15 through 24, 1997). In both model runs and actual operations, if water is released from Jennings Randolph Reservoir and demand is lower than predicted, then flow exceeds the minimum flow recommendation. (From the water supplier perspective, this is an inefficient operation, but it should be noted that the variation in flow echoes natural variability and can be viewed as a net benefit to the environment.) Alternatively, if water is released from Jennings Randolph Reservoir and demand is higher than predicted, then the extra demand must be met with releases from Little Seneca Reservoir, requiring a day of travel time to the most downstream water supply intake. In operations and model algorithms, the storage remaining in Jennings Randolph and Little Seneca reservoirs is managed by conjunctive use algorithms.

RESULTS OF RESOURCE ADEQUACY ANALYSIS

Results from the most recent resource analysis conducted in 2005, indicate that the existing system can meet forecasted 2025 through 2045 water supply demand during a repeat of the drought of record (1930) without depleting all reservoir storage (Table 6). Various scenarios were examined to explore the sensitivity of the system, including development of a stochastic streamflow record to explore how the system would respond to a drought more severe than that in the historical record (Table 6). The system meets forecasted 2020 demand throughout a simulation of 500 years of stochastic streamflow, although mandatory restrictions are required in 1.1 percent of years and emergency restrictions are implemented in 0.6 percent of years.

TABLE 6. Results of Year 2000 Demand Forecast Study.

Scenario	Minimum Combined Water Supply Storage in All Reservoirs, Billion Gallons, Plus or Minus One Standard Deviation (percent full)
“Most likely” estimate of 2025 demands, simulation of historical streamflow record	12.0 ± 0.2 (23 percent)
“High” estimate of 2025 demands, simulation of historical streamflow record	10.3 ± 0.4 (20 percent)
“Most likely” estimate of 2045 demands, simulation of historical streamflow record	6.7 ± 0.3 (13 percent)
“Most likely” estimate of 2020 demands, simulation of 500 years of synthetic (stochastic) streamflow	2.0 ± 0.2 (6 percent)

Note: Data from Kame´enui *et al.* (2005).

BENEFITS OF FIVE-YEAR CYCLE

The five-year interval provides benefits obviously realized for the demand forecast, as the interval is appropriate for capturing changes in demographic trends and projections and updating the unit use numbers using observed quantities. The interval is just as important for the resource adequacy analysis as discussed in more detail below.

Improvements to Modeling Tools and Understanding of Physical System

The five-year interval is influential for the resource adequacy analysis, allowing significant improvements in the methodology and improved understanding of the physical system to be incorporated into subsequent analyses. As each study is conducted, questions about the physical system are raised that can be investigated and then incorporated into the next round of analysis.

In 1999, actual drought operations showed that the travel time from Jennings Randolph Reservoir to the downstream water supply intakes is approximately nine days, much longer than the four to five days originally assumed (Trombley, 1982). As the lead time for release decisions is longer, so is the uncertainty of demand and weather forecasts. As the Jennings Randolph release travels to the water supply intakes, a chance thunderstorm somewhere downstream in the basin can cause Potomac flow to increase, erasing the need for the water supply release. Since releases must be made based on both weather and demand forecasts, the accuracy of release decisions is diminished, causing reservoir storage to be depleted more quickly than it would otherwise. This decreased efficiency of reservoir operations was incorporated into the 2000 study (Hagen and Steiner, 2000).

Another critical question is the level of upstream consumptive water use. Given that the Potomac River basin upstream of the WMA is not heavily populated, resource adequacy analyses done in 1990 (Holmes and Steiner, 1990) and 1995 (Mullusky *et al.,* 1996) assumed that upstream consumptive use was insignificant. This assumption was examined in a study sponsored by the Maryland Department of the Environment that estimated current and future consumptive use in the basin due to industrial, commercial, municipal, thermoelectric, mining, livestock, and irrigation demand (Steiner *et al.,* 2000). The study found that consumptive use in 2000 upstream of the WMA was significant, estimated at 129 mgd (0.49 million m^3/d) for a hot and dry summer day and expected to grow to 149 mgd (0.56 million m^3/d in 2020. This understanding of the significance of consumptive water use was incorporated into the resource analysis study conducted in 2000 (Hagen and Steiner, 2000). Historical river flows were adjusted to account for current and projected levels of upstream consumptive use. This reduction in historical flows during the critical drought period of 1930 affected decreased the projected time when resources may be stressed.

After the 2000 study (Hagen and Steiner, 2000), the decision was made to more explicitly model the water quality operations of the Jennings Randolph Reservoir and Savage Reservoir in the North Branch Potomac basin. These reservoirs are operated by the USACE for water quality improvements by increasing summertime low flows with releases typically in the 150 mgd to 300 mgd (0.5 million to 1 million m^3/d) range. When water supply releases are called for by CO-OP, the USACE typically reduces its water quality release to 77 mgd (0.29 million m^3/d). The version of PRRISM used in the 2000 study (Hagen and Steiner, 2000) conservatively assumed the minimum release from water quality storage at all times. Since that time, substantial effort went into the calibration of a model of the USACE's North Branch water quality operations that was incorporated into the current version of PRRISM. North Branch water quality operations usually result in higher releases from the North Branch than the minimum 77 mgd (0.29 million m^3/d) release, which offsets the timing and magnitude of reservoir releases needed from water supply storage. Including the effects of North Branch water quality operations increases historical yield by approximately 29 mgd (0.11 million m^3/d).

When regulatory, environmental, or other water quantity questions are raised, the tools, expertise, and results are immediately accessible and information is available to answer questions about water supply and river flow. Without this ongoing commitment to assessment of system resources, such analyses would be difficult to conduct in a timely manner.

Improvements in Policy and Management

Policy and management questions were raised and addressed in successive demand and resource studies. Each study improved through the dialogue facilitated through interaction with the stakeholder community.

A key policy/management question examined by utility managers was whether to plan to meet unrestricted demand. The 1990 (Holmes and Steiner, 1990) and 1995 (Mullusky *et al.,* 1996) planning studies assumed unrestricted demands when assessing the ability of resources to meet projected demands. During quarterly meetings of the water suppliers at

ICPRB prior to the 2000 demand study (Hagen and Steiner, 2000), water managers began discussing trade offs between periodic restrictions during drought years and gains in long term water supply reliability. Before this discussion could be resolved, actual drought events intervened. During the drought of 1999, the governor of Maryland established statewide mandatory restrictions. These restrictions were implemented uniformly across the state. These restrictions were in conflict with an assessment by water managers in the WMA that the available supply was more than adequate to meet current levels of unrestricted demands. Elected officials in Virginia and Washington, D.C., chose not to implement restrictions in the WMA, citing the water managers' assessment of resource reliability. Residents on the Washington, D.C., side of Eastern Avenue could water lawns, but those on the Maryland side could not, which was confusing to the public since all jurisdictions used the same source of water. While restrictions would not increase Potomac River flow (the river is controlled to meet a minimum flow recommendation), restrictions would increase the amount of storage left in Little Seneca Reservoir in Montgomery County, Maryland.

Little Seneca Reservoir had not been used as a water supply reservoir since its construction in 1981. The area surrounding the reservoir had been developed with townhouses and single-family homes, and the lake itself had become a valuable local recreational resource. Montgomery County politicians preferred not to use the water supply reservoir until water users in Maryland, Washington, D.C., and Virginia (all of whose residents had paid for the construction of the reservoir) restricted their water use. While issues of equity and fairness were debated, the controversy was eventually ironed out in closed door meetings of the WMA politicians, who agreed to implement restrictions per a compromise that was codified in a regional drought plan (MWCOG, 2000). While water resource managers would prefer that the compromise be motivated by more idealistic concern over long-term water supply reliability, the accommodation of recreational interests and homeowner property values at Little Seneca Reservoir through the regional compromise has a corollary benefit: it increases the long-term water supply reliability with a relatively minor reduction in level of service. The resource assessment of the 2000 demand study (Hagen and Steiner, 2000) was modified to mirror this regional policy, modeling voluntary reduction in demand when the reservoirs reached 60 percent full. Future water resources modeling and analysis could be done to more explicitly examine the tradeoffs among various demand reduction triggers and gains in water supply reliability and implemented through an educational campaign.

The relatively short interval between studies allows sufficient time to begin the planning process for meeting future water supply needs in the event a shortfall is forecast. The conclusions of the 2000 study (Hagen and Steiner, 2000) state that under the most likely growth scenario, current resources met 2020 levels of demand with about 18 percent remaining storage in the Potomac reservoirs and met 2030 demands with about 9 percent remaining. That modeled reservoir storage dropped to relatively low levels was enough to trigger evaluation of water supply alternatives. Water managers did not wish to fully deplete reservoir storage, even in a planning context, and as a result began exploring various water supply alternatives in feasibility studies. FCWA led a study funded by the USEPA of the viability of several new water supply alternatives such as the use of an abandoned quarry for water supply storage. Concurrently, and at the request of the WMA water suppliers, CO-OP investigated the feasibility of improvements to operational efficiency, regional benefits associated with various structural alternatives, and demand management alternatives. The subsequent 2005 study (Kame´enui *et al.,* 2005) showed that the existing system remains adequate to meet future demand through 2025.

Interaction With Stakeholder Community

The iterative and cooperative nature of this work enhances regional understanding of the WMA water supply issues and provides a comprehensive body of knowledge about regional water supply reliability. The five-year cycle provides a rationale for CO-OP interaction with utilities, planning agencies, and interested stakeholders for substantial information input, further integrating them into the process.

CO-OP's involvement with the League of Women Voters' study of water supply is an example of this interaction with stakeholder groups outside the water utilities. The League of Women Voters used the results of the 1995 resource adequacy study (Mullusky *et al.,* 1996) as a motivation and basis for its report on water supply prospects and options in the WMA for the 21st Century (League of Women Voters of the National Capital Area Water Supply Task Force, 1999). The report, developed with input and participation from CO-OP staff, included several recommendations for improvements to future resource adequacy studies by CO-OP. Suggestions included: (1) incorporating changes in predicted per capita water use over time due to the effects of conservation, especially with regard to water conserving technologies mandated by the Federal Energy Policy Act of 1992; (2) modeling the effects of reduced demand due to the effects of voluntary and mandatory water use restrictions; (3) addressing reservoir siltation as a factor in reducing the volume of storage available in future years; and (4) providing a more sophisticated treatment of the level of detail of modeled upstream reservoir operations in the resource analysis. While these improvements were already planned by CO-OP for the 2000 study that was then under way, the interaction between CO-OP and the League of Women Voters enabled a collaborative understanding of the issues at hand and enhanced regional support of the overall study process.

CONCLUSIONS AND FUTURE WORK

The five-year interval has proven to be rewarding. Taken together, the studies present an evolving understanding of regional water supply reliability and are the basis of a comprehensive body of knowledge. The iterative nature of the work allows for a forum for cooperation and interaction among the WMA water suppliers and provides regular updates and incorporation of recent demographic forecasts.

For the time between studies, the tools and expertise that are developed for the demand studies are immediately accessible (they are maintained and improved for use in the next study) and can be used or modified to answer regulatory, environmental, or other water quantity questions as they arise. The interval provides an opportunity to reevaluate previous assumptions, both technical and policy, triggered by multiple passes at the resource adequacy analysis. Research and refinement of the technical tools is pursued with input from various experts, allowing significant improvements in the methodology and improved understanding of the physical system to be incorporated into subsequent analyses.

Policy and management questions are raised and addressed in successive demand and resource studies. Each study is improved through the dialogue between policy and engineering that is facilitated through interaction with the stakeholder community. The iterative and cooperative nature of this work enhances regional understanding of the WMA water supply issues by the stakeholder community, keeping the public and local governments involved and informed on regional water supply issues.

In the event that future resources are found wanting, the interval provides an adequate lead time for the water utilities, ICPRB, and other stakeholders to begin planning for new water supply alternatives. The same tools used in the studies for the resource assessment can be used to evaluate the system benefits of water supply alternatives.

Future demand and resource studies will continue to consider a stochastic analysis to quantify the risks of experiencing a drought that is more extreme than the historical observed droughts, to better quantify the versatility of the existing system. While such an analysis will not directly address or quantify possible changes due to climate variability or climate change, this analysis will begin to address the additional uncertainty introduced by potential changes in climate on the management of water resources and will allow for testing alternative designs and policies against a larger range of flow sequences that are likely to occur in the future beyond that of just the historical flow sequence (Loucks *et al.,* 1981). Additional study is warranted to examine the effects of variability of climate on WMA water resources.

Prior studies used unit use methods for demand forecasts. Because past studies show that resources may be strained in the future due to demand growth, it is appropriate to consider more comprehensive forecast methods. More comprehensive studies can be useful for evaluating demand-side management strategies such as pricing or conservation alternatives and can provide a more quantitative evaluation of risk and uncertainty.

Future work could be done to more explicitly examine the tradeoffs between various demand reduction triggers and gains in water supply reliability and implemented in an educational campaign. Such is the opportunity afforded in the intervals between demand studies.

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